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Pasteurization of shell eggs using radio frequency heating☆

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ABSTRACT

The USDA-FSIS estimates that pasteurization of all shell eggs in the U.S. would reduce the annual number of illnesses by more than 110,000. However, less than 3% of shell eggs are commercially pasteurized. One of the main reasons for this is that the commercial hot water process requires as much as 60 min to complete. In the present study, a radio frequency (RF) apparatus was constructed, and a two-step process was developed that uses RF energy and hot water, to pasteurize eggs in less than half the time. In order to select an appropriate RF generator, the impedance of shell eggs was measured in the frequency range of 10–70 MHz. The power density within the egg was modeled to prevent potential hotspots. *Escherichia coli* (ATCC 35218) was inoculated in the yolk to approximately 7.5 log CFU/ml. The combination process first heated the egg in 35.0 °C water for 3.5 min using 60 MHz RF energy. This resulted in the yolk being preferentially heated to 61 °C. Then, the egg was heated for an additional 20 min with 56.7 °C water. This two-step process reduced the population of *E. coli* by 6.5 log. The total time for the process was 23.5 min. By contrast, processing for 60 min was required to reduce the *E. coli* by 6.6 log using just hot water. The novel RF pasteurization process presented in this study was considerably faster than the existing commercial process. This should lead to an increase in the percentage of eggs being pasteurized, as well as a reduction of foodborne illnesses.

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1. Introduction

Shell eggs and egg products were ranked the second riskiest food regulated by the FDA, and were linked to 352 outbreaks from 1990 to 2006 (Klein et al., 2009). *Escherichia coli*, including extra-intestinal pathogenic *E. coli* (ExPEC), has been isolated from eggs (Englmaierova et al., 2014; Mitchell et al., 2015). The USDA-FSIS estimates that pasteurization of all shell eggs in the United States (i.e., reducing the bacterial population by 5 log) would decrease the annual number of illnesses by more than 110,000 (Schroeder et al., 2006).

Currently, only two companies in the U.S. pasteurize shell eggs. They both use hot water immersion whereby the eggs are submerged in water at an elevated temperature for approximately 60 min (Day, 2010). There are two reasons for the lengthy time required for the commercial hot water process. The first is the limiting temperature of the water. The foaming power of albumen begins to decline when momentarily subjected to a temperature of 57 °C (Cunningham, 1995). Van Lith et al. (1995) immersed shell eggs in hot water and determined that 57 °C is the maximum water temperature that can be used without coagulating the albumen. Pathogenic bacteria are not quickly inactivated at 56.7 °C. The U.S. Department of Agriculture's required minimum holding times for pasteurizing liquid yolk are 6.2 and 3.5 min at 60.0 and 61.1 °C, respectively (USDA, 1969). At a temperature of 56.7 °C, the pasteurization holding time is estimated to be 35 min (USDA, 1969). Based on the results of Humphrey et al. (1990), who determined the *D*–values of *Salmonella* in egg yolk at 55 and 60 °C, the *D*–value at 56.7 °C is approximately 7.4 min (Geveke et al., 2016). The second reason for the protracted hot water process is that the heat must first be transferred from the water to the shell, and then, by conduction, from the shell to the heat-sensitive albumen, and finally to the yolk. The come-up time (i.e., the time required to raise the yolk temperature to 57 °C) is 20 min or longer (Cox et al., 1996; Geveke et al., 2016; Park and Cho, 2006; Stadelman et al., 1996). The lengthy

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hot water immersion process contributes to the cost of commercially pasteurized eggs. In some cases, adding more than $1 to the price of a dozen eggs (Sinclair, 2012).

Alternative techniques for pasteurizing shell eggs have been researched, but only one of these has been commercialized. This process uses microwave energy and is practiced only in South Africa (Wiid, 2008). Microwave energy can penetrate into the shell egg and heat up the yolk faster than hot water. However, the penetration depth of microwaves (915 and 2450 MHz) in foods can be as low as 0.3 cm (Tang et al., 2004). This means that very little microwave energy may make it to the yolk. The patent, which forms the basis of the South African microwave process, indicates that the method takes approximately 30–40 min and results in a bacterial reduction of between 2 and 5 log (Erasmus and Rossouw, 2008). In addition, the process causes a slight haziness of the albumen and a reduction in whipping ability (Wiid, 2008).

Penetration depth of electromagnetic energy is inversely dependent on the frequency. Thus, radio frequency (RF) energy, which ranges from 10 to 300 MHz (Orfeuil, 1987), can have a penetration depth ten times greater than that of microwave energy (Tang et al., 2004). The deeper penetration of RF energy should heat the yolk better than microwave energy and prevent loss of albumen quality. The use of RF energy to pasteurize shell eggs is discussed very little in the literature. Hamid-Samimi et al. (2002) reveal the use of RF energy to rapidly pasteurize egg products. However, the majority of their patent deals with processing liquid egg products and scant information is given regarding shell eggs. More recently, Dev et al. (2012) modeled the heating of shell eggs in a parallel plate RF applicator. The modeling showed that heating would be highly nonuniform and may lead to the generation of hot spots in the albumen. The modeling also indicated that rotating the eggs would reduce the nonuniformity; however, these results were not experimentally validated. Kannan et al. (2013) heated eggs with a parallel plate RF applicator to 56 °C. Coagulation of the albumen was avoided, but only by prolonging the heat-up time to 45 min which approaches the time required for conventional hot water processing. In addition, no microbiological testing was performed.

RF energy, applied with a unique converged applicator, has been used to pasteurize apple cider and orange juice with minimal effects on quality (Geveke et al., 2007; Geveke and Brunkhorst, 2008). Research is needed to determine if shell eggs can be pasteurized using RF energy, applied in a more precise manner rather than by a simple parallel plate applicator. The present study developed a RF applicator that placed the egg in direct contact with curved electrodes. The equivalent circuit of the egg and electrodes is a series RC circuit. The resistance (R) is composed of the conductive albumen and yolk, while the capacitance (C) is due to the egg shell acting as a dielectric. Application of RF to the electrodes creates electric fields in both the resistive and capacitive portions of the egg. Due to the conductive nature of the albumen and yolk, power is dissipated ohmically. By closing the gap between the electrodes and the shell, the capacitance of the RC circuit is increased. Thus, a lower voltage at the electrodes is required to maintain the same degree of heating, and the potential for hotspots in minimized. Most commercial RF power systems operate at a source impedance of 50 Ω. For maximum power transfer, the load impedance should match the source impedance. The optimum frequency for impedance matching would be where the series impedance of the egg/electrode circuit would be closest to a value of 50 + j0 Ω. The intention of using this RF applicator is to gently pasteurize shell eggs in less time than using the conventional hot water immersion method with the aim of increasing the percentage of eggs pasteurized in the U.S. and reducing foodborne illness.

The major goals of this study were to: (1) design and assemble an apparatus to apply RF energy to a shell egg in a controlled fashion; and (2) develop a process for pasteurizing shell eggs using RF energy. To these ends, additional objectives included measuring the impedance of a shell egg and modeling the power density within the egg during RF processing.

2. Materials and methods

Escherichia coli (ATCC 35218), a surrogate for *Salmonella*, was maintained on tryptic soy agar (TSA; Becton, Dickinson and Company, Franklin Lakes, NJ) at 4 °C. The *E. coli* was cultured in tryptic soy broth (Becton, Dickinson and Company) with shaking at 37 °C for 16–18 h.

Shell eggs were obtained from a local commercial egg producer. Eggs were sorted to obtain eggs weighing 61–64 g each and were stored overnight at room temperature (23 °C) prior to being inoculated.

The large ends of the eggs were first perforated by hand with an 18 gauge sterile needle (Becton, Dickinson and Company). Following shell perforation, eggs (with the large end up) were placed in an inoculation device (designed and assembled in-house) that precisely injected the *E. coli* inoculum into the geometric centers of the yolks. The device was comprised of a Hamilton, Gastight model 1725LT, luer tip, autoclavable, 250 μl glass syringe (Hamilton Co., Reno, NV) and a 16 gauge, 3.8 cm needle (Beckton-Dickson) that were clamped to a low-speed, battery-powered actuator. The glass syringe was filled with the inoculum and centered over the hole in the large end of the egg. The actuator slowly pushed the tip of the needle through the hole to a depth of 3.2 cm and into the center of the yolk. Eggs were then slowly injected with 50 μl of inoculum. This was followed by a 30 s delay to permit pressure equilibration within the egg to prevent inoculum leakage from the yolk. The actuator then slowly retracted the needle and the egg hole was sealed with a drop of fast-curing epoxy gel (1 Minute™ #14277, ITW Devcon, Danvers, MA) and allowed to cure for at least 30 min before thermal treatments. The population of *E. coli* in the whole egg was measured at approximately 7.5 log CFU/ml (positive control).

Preliminary trials using a dye technique were done to confirm that cultures were inoculated into the geometric center of the yolks (Brackett et al., 2001). This technique consisted of injecting 50 μl of dye into the egg followed by a standard hard-boiling procedure to demonstrate consistent placement of the dye near the center of the yolk with no discernible drift (as shown in Fig. 1).

For treatment with RF, a unique apparatus was designed and assembled in-house. The apparatus comprised an electrode that

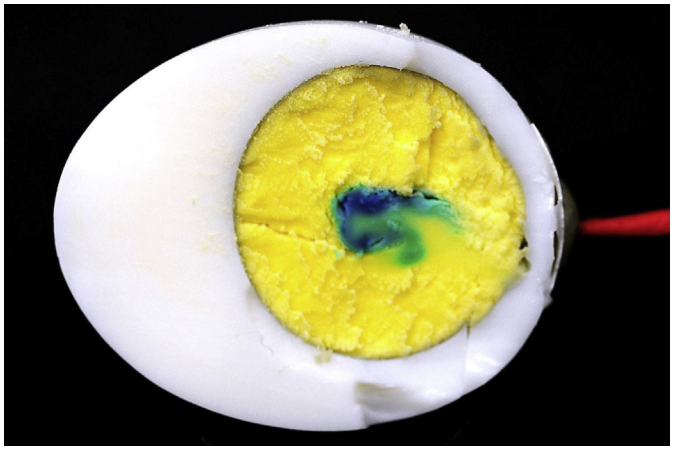

Fig. 1. Cross-section of a hard-boiled egg that had been injected with dye, to confirm the placement of inoculum at the center of the yolk.